Inter-Laboratory Comparison of Luminous Intensity Distribution and Total Luminous Flux Measurements with Far Field and Near Field Goniophotometry

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***Abstract*--In order to be recognized as a competent testing and calibration laboratory, metrology laboratories who aim to obtain an accreditation for specific tests need to fulfill a number of general requirements as stipulated in the International Standard ISO/IEC17025. One way to assure the quality of testing is to participate in proficiency testing programs or to conduct inter-laboratory comparisons. In this paper, luminous intensity distribution measurements of three LED lamps, performed in two metrology laboratories according to the CIE and IESNA standard guidelines, are presented and compared. Significant differences are found for LID results of a directional lamp, due to high-dynamic range issues being observed in the near-field goniophotometer. It is also detected that the correlated color temperature influences the illuminance measurement of the photometer in the goniophotometer.**

***Index Terms*-- Far-field goniophotometry, high-dynamic range, luminous intensity distribution, near-field goniophotometry.**

I. Introduction

LIGHTING industry and lighting design require measurements of both the luminous intensity distribution (LID) and the total luminous flux. The LID is measured with a goniophotometer, consisting of a detector recording the irradiance/illuminance at various angles around the device under test (DUT). Previously the goniophotometers were associated with enormous footprints (volumes >> 500 m^3) in order to accomplish the point source approximation, i.e., far-field goniophotometry. With the advent of imaging systems based on silicon photonics, adoption of charge-coupled device (CCD) cameras in goniometer measuring systems has become possible. This provides a number of advantages, such as: distance regardless measurement of light sources' LID's, determination of starting point and direction of the rays emitted by light sources, and determination of far field parameters (luminous flux and intensity distribution) of light sources [1]. As such, near-field goniophotometry has gained popularity in lighting industry over the past 10 years.

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Lighting metrology laboratories who aim for accreditation under ISO/IEC17025 must follow proficiency testing programs and perform inter-laboratory comparison in order to assure their technical competence [2]. However, at the time this work is written, no standard procedure exists to perform inter-laboratory comparisons of LID measurements performed with both far-field and near-field goniophotometers.

This work presents the results of such an inter-laboratory comparison performed among two laboratories: the Light & Lighting Laboratory of KU Leuven (Belgium), being equipped with a near-field goniophotometer, and the Laboratory for Industrial Testing Fabio Chaparro of the National University of Colombia (Colombia), which possesses a far-field goniophotometer. The method followed to measure the LID and to calculate the uncertainty propagation across the inter-laboratory comparison for the LID and the luminous flux, as well as the results from the comparison, are discussed.

II. Methods

A. Measuring equipment

At the Light & Lighting Laboratory, which will further be denoted as the nucleus lab, the LID of the DUTs (see further) was measured with a near-field goniophotometer Technoteam RIGO801-300. The near-field goniophotometer possesses a luminance camera and a photometer. For each position a relative luminance image was captured and scaled with the total luminous flux measured with the photometer. Nevertheless, the near-field goniophotometer was also used in the far-field mode considering the sample size – distance to the detector ratio larger than 30. The electrical parameters are recorded with a calibrated Power Analyzer (Yokogawa WT3000). Measurements are carried out under an ambient temperature of 25 ± 1 ºC.

At the Laboratory for Industrial Testing Fabio Chaparro, further denoted as the satellite lab, the LID of the DUTs was measured with a far field goniophotometer LMT GO-DS 2000, and the electrical parameters with a power analyser Yokogawa WT1600. Measurements were carried out under an ambient temperature of 24.5 ±0.5 ºC.

ISBN 978-85-86923-36-4

B. DUTs

Three light sources were chosen for measurement, based on the directionality of their distribution and the correlated color temperature (CCT). They correspond to a directional LED luminaire with abrupt changes in the intensity distribution (DUT1), an omnidirectional LED lamp with CCT of 2700 K (DUT2), and an omnidirectional LED lamp with CCT of 6000 K (DUT3) (See Fig. 1). Information about the operating conditions for each DUT are summarized in Table 1.

Fig. 1 DUTs: a) directional lamp (DUT1), b) omnidirectional lamp CCT 2700K (DUT2), c) omnidirectional lamp CCT 6000 K (DUT3)

Table 1 Operating conditions of each sample under test

	DUT1	DUT2	DUT3
Product reference	Duell wall – Modular	MasterLEDbulb – Philips	Globe, 21 SMD – Conrad
Rated voltage [V AC]	230	230	230
Frequency [Hz]	50	50	50
Rated power [W]	2	12	2.5
Nominal Luminous Flux [lm]	---	806	250
Nominal CCT [K]	3000	2700	6000
Luminous efficacy [lm/W]	---	67	100

C. Measurements

The parameters measured for each DUT are the LID, the total luminous flux (Φ), the active and apparent power, and the power factor. To align the C-0 plane, the samples were marked in the nucleus lab indicating the C-0. The driving software of each laboratory differs in the coordinate system definition, while the nucleus lab follows the CIE system, the satellite lab does the IESNA. Such a difference represents 90º in the definition of the C-0 plane. Thus, the mark of C-0 plane defined at the nucleus laboratory was aligned with the C-90 plane at the satellite laboratory.

Measurements were performed after thermal stabilization, according to the stability criteria defined in LM-79-2008; i.e., the variation of at least three readings of the light output and electrical power over a period of 30 min, taken 15 minutes apart, is less than 0.5 %.

All LIDs were measured within the following range of C-planes and γ angles: $0° \le C_{plane} \le 360°$ and $0° \le \gamma \le 180°$. Scanning resolution was 1 ° for both γ and C angles.

D. Reporting results

The measured LIDs are reported in the IES format.

In order to compare the equivalent LIDs, two metrics $F_{lum,flux}$ and $F_{lum,fit}$, proposed by Bergen [2], are used. $F_{lum,flux}$ is defined as the ratio of the total luminous flux of the DUT measured at the nucleus lab, to the total luminous flux of the DUT measured at the satellite lab:

$$F_{lum,flux} = \frac{\Phi_N}{\Phi_S}$$

$F_{lum,fit}$ quantifies the difference between the LIDs by comparing the intensity values measured at each (C,γ) position. According to Bergen, an index value of 98 corresponds to a good agreement, and a value over 99 a very good agreement.

$$F_{lum,fit} = 100 \times \left(1 - \sqrt{\frac{\sum_0^{360}\sum_0^{180}\left[I_N(C,\gamma) - I_S(C,\gamma)\right]^2}{\sum_0^{360}\sum_0^{180}\left[I_N(C,\gamma) + I_S(C,\gamma)\right]^2}} \right)$$

III. Results and discussion

Each DUT was driven by the conditions summarized in Table 1, which were reproduced within a variation margin smaller than 5% as summarized in Table 2. Each lab declares an uncertainty of the electrical parameters smaller than 2 %. Hence, existing differences in the measured optical parameters are independent of the supply conditions.

Table 2 Electrical parameters. N. and S. refer to Nucleus and Satellite, respectively

	DUT1		DUT2		DUT3	
	N. Lab	S. Lab	N. Lab	S. Lab	N. Lab	S. Lab
Stabilization time [min]	33	60	30	45	30	45
Active power [W]	6.51	6.29	12.5	12.65	2.46	2.49
Apparent power [VA]	16.8	17.4	15.4	15.6	11.1	11.1
Power factor [---]	0.38	0.36	0.81	0.81	0.22	0.22

Measurement of the optical parameters for each lamp was carried out only after thermal stabilization, which took between 30 and 60 minutes for each DUT. Once reached the steady state condition and throughout the measurement the environmental conditions were kept constant (25º± 2º) at both labs.

The total luminous flux of the three lamps, calculated by numerical integration of the illuminance measurements at each (C,γ) position, is summarized in Table 3.

Table 3 Luminous flux measuring results

	DUT1	DUT2	DUT3
N. Lab NF (1) Φ [lm]	129.6	769.7	263.8
N. Lab FF (1) Φ [lm]	128.2	772.6	-----
Satellite Lab Φ [lm]	123.6	767.9	255.5
Nucleus Lab (2) Φ [lm]	129.6	763.3	264.4
Relative difference	4.6%	0.2%	3.1%

LID of the DUT1 is presented in the inset of Fig. 2 for four different C-planes in polar coordinates, and in rectangular coordinates for C-0 plane in the main frame. Results from the nucleus lab are denoted as “N. Lab” and colored with a dotted blue line and a continuous orange line for the near- and far-field, respectively. Results from the satellite lab are denoted as “S. Lab” a colored with a dashed red line.

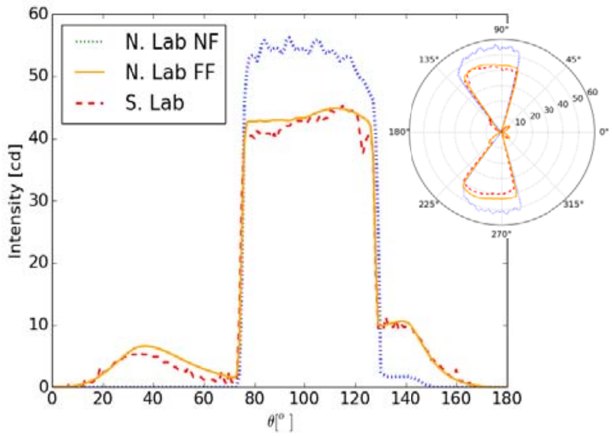

Fig. 2 LID of the directional lamp Duell wall – Modular (DUT1)

For angles around γ 0º and 180º the satellite lab measured values higher than the nucleus laboratory. The sharp changes in the radiation pattern exhibited around the angles γ 0º and 180º demand a high dynamic range for the measuring equipment. Such dynamic range conditions are fully supported by the far field goniophotometer, whose dynamic range only depends on the photometer. Conversely, the near field goniophotometer dynamic range is defined by both the photometer and luminance camera. While the dynamic range for certain integration time of the photometer is 18 bits (S/N ratio 108 dB), the one for the luminance camera is only 12 bits (S/N ratio 72 dB). If the dynamic range of the lamp under test is broader than the luminance camera’s and saturation is avoided, some values are ignored by the luminance camera observation. Since the luminance image for each position will be scaled with the total flux measured by the photometer, some values will be overestimated, as can be seen on Fig. 2. Such a drawback of the near-field goniophotometry’s current status was predicted by [3] and experimentally confirmed by [4].

Besides to the error attributed to the dynamic range, misalignment in the C-plane of approximately 2° is also evident in Fig. 2.

LID of the DUT2 in both rectangular and polar coordinates are presented in the Fig. 3 main frame and inset, respectively.

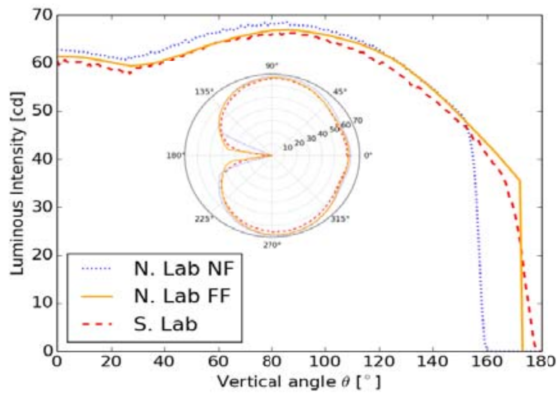

Fig. 3 LID of the omnidirectional lamp MasterLEDbulb – Philips (DUT2)

For the case of the DUT2, the low dynamic range of the luminance camera relapses for the values around γ=180º measured at the nucleus lab with the near-field goniophotometer.

The LID of the DUT3 in Fig. 4 shows a good agreement between both labs.

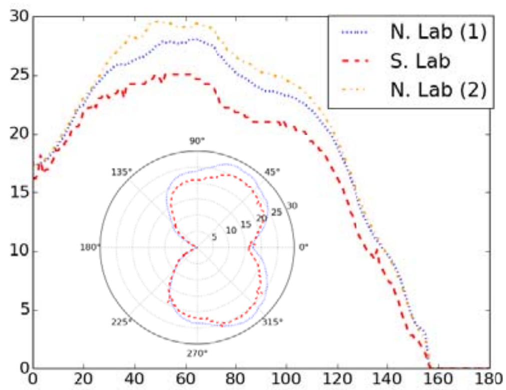

Fig. 4 LID of the omnidirectional lamp Globe, 21 SMD – Conrad (DUT3)

ISBN 978-85-86923-36-4

Despite the reproducibility of electrical parameters and environmental conditions, variations higher than 3 % were detected in the total luminous flux values derived from the measurements at both labs (See Table 4). Similarly, the LIDs in Fig. 2-Fig. 4 exhibit significant variations, that are quantified via the indexes defined in the Methods section. Results of the LID fit, $F_{lum,fit}$, for each lamp are summarized in Table 4.

TABLE 4 COMPARATIVE INDEXES OF THE OPTICAL PARAMETERS

	DUT1	DUT2	DUT3
$F_{lum,fit} - NF$	83.5	94.9	96.5
$F_{lum,fit} - FF$	88.2	96.7	96.5
$F_{lum,flux}$	1.06	1.02	1.05
$F_{lum,fit2}$	88.2	96.9	97.7

The $F_{lum,fit}$ was calculated for the near- and far-field measurements at the nucleus lab, labeled as $F_{lum,fit} - NF$ and $F_{lum,fit} - FF$, respectively.

The LID for the three samples was corrected for the mismatch in the total luminous flux, and the fit factor $F_{lum,fit}$ was recalculated. The new fit factor is presented as $F_{lum,fit2}$ in the Table 3.After the correction, the sample on which the total luminous flux mismatch has a higher impact is the third one, whose fit factor changed from 96.5 to 97.7, closely to the merit figure defined for such an index. Considering the CCT of this sample was significantly high (6500 K), one of the causes of the total luminous flux mismatch can be the $V(\lambda)$ calibration curve loaded into the photometer's software.

Despite the good correspondence between the far field measurements at the nucleus and satellite labs for the DUT1 in Fig. 2, the $F_{lum,fit}$ calculated from the data is far from reaching the merit function value. This insinuates that the low $F_{lum,fit}$ is mainly attributed to the mismatches between LID measured at the other C-planes, where the intensity values are very low. Since the intensity values become low at C-planes different from C-0/C-180, the signal to noise ratio decreases, and the error increases.

In order to verify that no variation occurred on the DUTs due to the transportation process, they were measured after coming from the satellite lab at the nucleus lab. Results for both total luminous flux and LID, labeled as Nucleus lab (2) in Table 3, show differences smaller than 1 , which ratify that transport process did not affect the inter-comparison results.

IV. CONCLUSIONS

Three samples were measured in two lighting laboratories overseas. Maximum differences of 13.3 % and 5.8 % were found for the fit index of the measured luminous intensity distribution and the total luminous flux derived from it, respectively. Largest difference occurred for the directional lamp when measured with the near-field goniophotometer, which was attributed to the limited dynamic range of the luminance camera. Results for the high color correlated temperature (6500 K) sample (DUT3) showed a mismatch in the photometric measurement, which is attributed to the photometer's incompetence to properly measure high amount of power concentrated towards the small wavelengths area (~450 nm) of the eye sensitivity curve under photopic vision $V(\lambda)$. Angular and positional misalignments showed also to be a cause of error, which could be treated via curve fitting after the measurements, or implementing a visualization system in the far field measurement setup.

V. ACKNOWLEDGMENT

This research was partially supported by Colciencias (National Department of Science, Technology and Innovation - Colombia) and the Flemish Hercules stichting (AKUL035).

VI. REFERENCES

[1] M Lopez et al., "LED near-field goniophotometer at PTB," *Metrologia*, vol. 49, no. 2, p. S141, 2012. [Online]. http://stacks.iop.org/0026-1394/49/i=2/a=S141

[2] ASJ Bergen, "A practical method of comparing luminous intensity distributions," *Lighting Research and Technology*, vol. 44, no. 1, pp. 27-36, 2012. [Online]. http://lrt.sagepub.com/content/44/1/27.abstract

[3] J Metzdorf, "Network and Traceability of the Radiometric and Photometric Standards at the PTB," *Metrologia*, vol. 30, no. 4, p. 403, 1993. [Online]. http://stacks.iop.org/0026-1394/30/i=4/a=036

[4] J. Audenaert, P. Hanselaer, and F. Leloup, "Practical limitations of near-field goniophotometer measurements imposed by a dynamic range mismatch," , 2014.

[5] Ferhat Sametoglu, "Influence of the spectral power distribution of a LED on the illuminance responsivity of a photometer ," *Optics and Lasers in Engineering* , vol. 46, no. 9, pp. 643-647, 2008. [Online]. http://www.sciencedirect.com/science/article/pii/S0143816608000808

VII. BIOGRAPHIES

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Peter Hanselaer was born in 1959 and received his Ph. D. in Physics at University of Gent(B) in 1986. Peter is associate professor at the University of Leuven. In 1997, he founded the Light & Lighting Laboratory specialized in spectral optical measurements. The mean research areas are lighting, colour and appearance, optical design, new light sources and photovoltaic energy. He is the Belgian delegate in the CIE, division 1. Peter is teaching physical topics of the master courses lighting and opto-electronics.

ISBN 978-85-86923-36-4